Physical Interfaces for Tabletop Games

J. LEITNER and M. HALLER
Upper Austria University of Applied Sciences
K. YUN and W. WOO
Gist, Korea
M. SUGIMOTO and M. INAMI
Keio University
and
A. D. CHEOK and H. D. BEEN-LIRN
National University of Singapore

IncreTable is a mixed-reality tabletop game inspired by *The Incredible Machine*. Users can combine real and virtual game pieces in order to solve puzzles in the game. Game actions include placing virtual domino blocks with digital pens, controlling a virtual car by modifying the virtual terrain through a depth camera interface, and controlling real robots to topple over real and virtual dominoes.

Categories and Subject Descriptors: H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems; H.5.3 [**Information Interfaces and Presentation**]: Group and Organization Interfaces—*Collaborative computing; computer-supported cooperative work*; K.8.0 [**Personal Computing**]: General—*Games*

General Terms: Design, Performance

Additional Key Words and Phrases: Mixed reality, interaction design, tabletop gaming, tangible user interfaces, pervasive games

ACM Reference Format:

Leitner, J., Haller, M., Yun, K., Woo, W., Sugimoto, M., Inami, M., Cheok, A. D. and Been-Lirn, H. D. 2009. Physical interfaces for tabletop games. ACM Comput. Entertain. 7, 4, Article 61 (December 2009), 21 pages.
DOI = 10.1145/1658866.1658880 http://doi.acm.org/10.1145/1658866.1658880.

Sponsored by the Austrian Research Studio NiCE (FFG) and by Team 7, AMS Research, and Sony DACC.

Contect authors' address: J. Leitner, Upper Austria University of Applied Sciences, Softwarepark 11, 4232 Hagenberg Austria; email: jakob.leitner@fh-hagenberg.at.

DOI 10.1145/1658866.1658880 http://doi.acm.org/10.1145/1658866.1658880

1. INTRODUCTION

Social and physical interactions are the new frontier in entertainment. Today, we build countless applications that provide entertainment to the masses, but very few of them support new user experiences.

For instance, Nintendo's Wii controller allows a very intuitive interaction and motivates people to have more fun playing games. On the other hand, people love traditional interfaces. In Europe, for example, traditional board games such as *Risk* and *Monopoly* are still highly popular. Instead of having a shoulder-to-shoulder experience playing a video game, people have a face-to-face communication experience [Magerkurth et al. 2004].

Interactive tabletop interfaces have emerged as an effective tool for colocated collaboration over digital artifacts [Scott and Carpendale 2006]. Related research shows that, at least in the case of collaborative work, a tabletop device can give a significantly higher job performance than a traditional desk. Moreover, it encourages a higher level of *creativity* and *interaction* among users [Scott and Carpendale 2006]. Not surprisingly, interactive tables also allow an optimal platform for many different games [Dietz et al. 2001; Tse et al. 2007]. Especially, when talking about role-based games, tabletop setups can be extremely interesting [Mandryk and Maranan 2002].

Over the past four years, we developed different tabletop games (see Figure 1), focusing mainly on interaction techniques [Buisine et al. 2007]. In this article we present our tabletop game, *IncreTable,* which is based on the mixed-reality game, *Comino* (see Figure 1(c)), as well as on related findings of an observational study of the game.

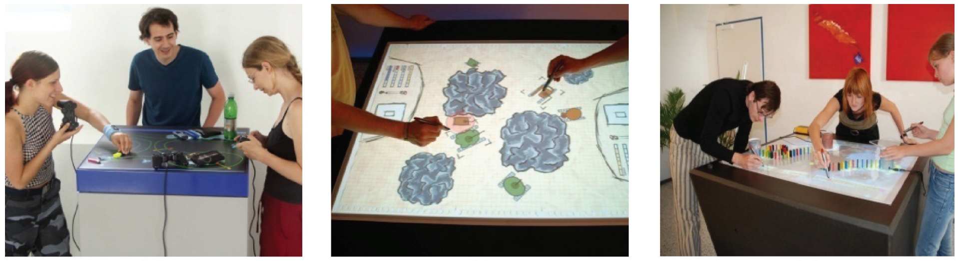
IncreTable is a tabletop game inspired by *The Incredible Machine*.[1] The original game was published by Sierra in 1992, building on the idea of a Rube Goldberg machine. The plan was to arrange a given collection of items in a needlessly complex way in order to solve a simple puzzle, thus provoking user creativity. Several publishers developed different versions (until 2001), but the original idea, that of solving puzzles, was never changed.

IncreTable (see Figure 2) is designed as a tabletop game and provides multimodal interaction based on bidirectional projection display, digital pens, a depth-sensing camera, and custom-made physical (tangible) objects and robots. Real-world objects provoke the user's active participation in creating content, which diffuses the boundary between the real and virtual worlds.

In summary, *IncreTable* has the following novel features:

- a novel combination of multimodal interactions based on new technologies;
- the provision of new experiences that dissolve the boundary between the virtual and real worlds;
- user-generated content through multiuser, interactive interfaces; and
- a bidirectional projection setup that allows content to be displayed in multiple levels.

[1]The Incredible Machine, http://en.wikipedia.org/wiki/The_Incredible_Machine



(a) (b) (c)

Fig. 1. Different tabletop games; (a) *NeonRacer* is an interactive car-racing game[2]; (b) *PenWars* is a sketch-based tank-war game[3]; and (c) *Comino* is a domino game that combines the physical and digital worlds [Leitner et al. 2009].

The amalgamation of the real and virtual worlds via our technological developments allow for a new, unparalleled gaming experience.

2. RELATED WORK

Over the past decade, tabletop games have become more and more popular [Kojima et al. 2006; Lee et al. 2005; Loenen et al. 2007]. In order to improve the social gaming experience, a tabletop setup that combines the advantages of a digital environment with the social impact of board games was proposed. In this setup, users can either use personal mobile devices or interact with the public tabletop display. All users sit face-to-face, share the same experience, and play in a new digital/real world. The game *MonkeyBridge*, presented by Barakonyi et al. [2005], extends the idea of Magerkurth et al. [2003]. They implemented a collaborative augmented reality game using head-mounted displays (HMDs). Users can use physical (tangible) objects, which have to be placed correctly, to guide digital augmented avatars. The rising popularity and availability of prototyping toolkits like Phidgets [Greenberg and Fitchett 2001], Arduino [Mellis et al. 2007], and games like *Lego Mindstorms* and their respective DIY (do it yourself) communities especially empower researchers to combine custom interfaces in games.[4] In the following section we briefly introduce selected relevant examples.

KnightMage is based on the STARS-platform [Magerkurth et al. 2003], and is played collaboratively by multiple users sitting around the STARS table. *KnightMage*'s hardware setup consists of a tabletop display and a wall display on which participants can share relevant information with other players. All the hardware components are part of the STARS platform, which is designed to support classical board games with the use of various multimedia devices. With the use of several displays, which can either be public or private, the STARS setup allows developers to create very complex game scenarios which can, for example, have both collaborative and competitive elements in one game. An embedded camera allows the system to detect and identify the game pawn on

[2]http://www.neonracer.net/
[3]http://mi-lab.org/projects/penwars/
[4]Make, http://www.makezine.com/

Fig. 2. *IncreTable* is a collaborative tabletop experience which allows playing with digital and real content simultaneously.

the interactive screen. In addition, the table includes RFID readers which, in combination with RFID tagged objects, can be used to save and load different scenarios and games.

Weathergods is a turn-based game that can be played by up to four players simultaneously on the Entertaible system [Bakker et al. 2007]. Each player has three different pawns that can perform different actions in the game. Wilson [2000] demonstrated in PlayAnywhere a flexible and transportable tabletop projection setup. Wilson [2007] also presented the pairing of a depth-sensing camera with an interactive tabletop to create a car racing game in which virtual cars race realistically over physical objects placed on the table's surface. *IncreTable* was influenced by this approach, since we wanted a physically correct behavior of the digital domino stones, which can be placed on any adequate surface.

3. INCRETABLE

Inspired by *The Incredible Machine*, the general objective of *IncreTable* is to arrange a given collection of items in a complex way in order to solve a puzzle. Each level presents a puzzle requiring multimodal interaction to encourage user creativity.

At each level of the game, users have to play with both digital and real objects. In Figure 3, for example, the goal of the level is to build a ramp with real objects. The physical objects on the table are tracked using a depth camera. A virtual car is projected from top onto the objects on the table. When the level is started, the car rolls down the ramp. The car's speed and direction are defined by the placement and height of the real ramp. The car itself has to cross the area under the physical tower (portal) which is then activated and topples over the row of real domino stones that can be seen in the front. Another physical portal detects whether all the dominoes have fallen down and tells the game whether the level has been cleared successfully.

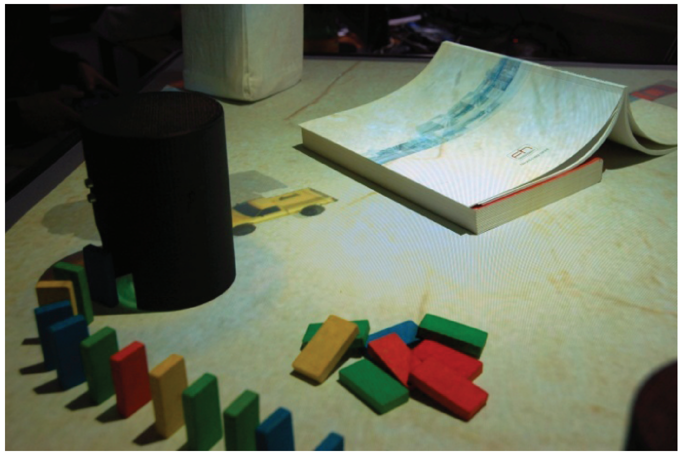
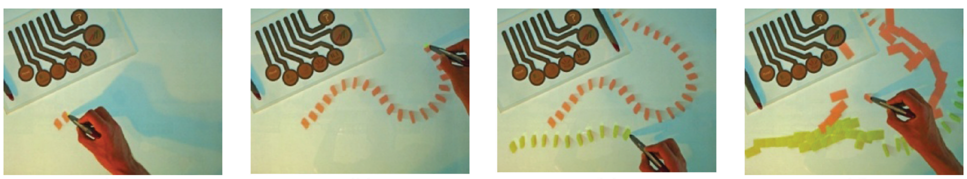


Fig. 3. Even folded paper books can be used to modify the terrain.



(a) (b) (c) (d)

Fig. 4. The digital domino pieces are placed with a digital pen. The use of a physics engine allows realistic interactions with other game components and the virtual environment.

Figure 3 also depicts a scenario where the players use everyday objects as game components. In this scenario, for example, the car jumps over real books, which are represented as ramps in the virtual terrain.

Other scenarios include setting up domino blocks in order to achieve certain goals in the level. In *IncreTable*, users cannot play with real domino stones only, but also with virtual ones. Using a wireless pen interface, players can draw a path on the table's surface for placing the digital (projected) domino tiles (see Figure 4). Since our system is based on a physics engine, even the digital tiles can topple down through awkward handling.

Players can select between different actions, set-up domino pieces, reposition, or delete domino pieces using a tangible toolbar. At the same time, other users can start setting up real domino pieces directly on the projection surface of the back-projection table, creating a very strong mixed-reality experience. While playing, users can move freely around the table. *IncreTable* has no dedicated mode for setting up the domino pieces. Hence, it happens quite often that either the real or the virtual domino pieces start toppling over before the chain reaction is started by the users, forcing users to concentrate and work together even more.

The use of physical game components also works as a catalyst to get players involved in the game. Since players are familiar with setting up real domino

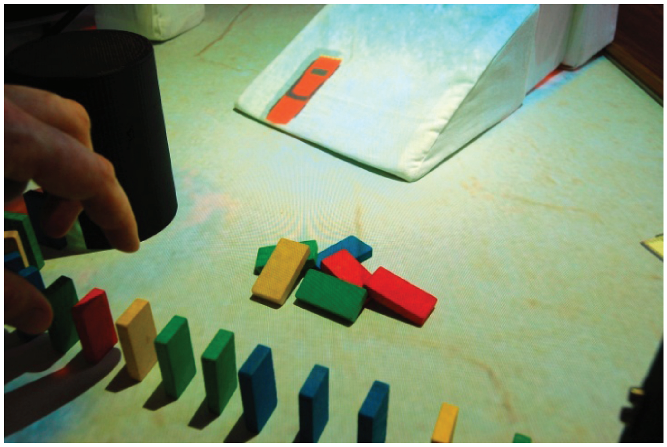


Fig. 5. Directly modifying the virtual terrain by moving physical objects or setting domino stones allows for an easy-to-use interaction.

stones even if they have no gaming experience, they can easily join a group of other players and get involved in the game (see also Figure 5).

4. IMPLEMENTATION

Figure 6 shows the hardware setup for *IncreTable*. The table hardware setup features a rear-projection screen with a Toshiba EX20 short-throw projector. Due to the projector's high lens offset, it is easy to use it in combination with only one mirror. The mirror and projector can simply be mounted at a 90° angle. The overall table box has a height (depth) of 550mm, with an operative screen size of 35.4″ × 26.75″ (900mm × 675mm). On top of the truss, we mounted a second projector for the tabletop projection and a depth-sensing camera for capturing the table's surface.

The two-projector setup allows for various novel display and augmentation techniques:

By displaying content on the rear projection screen, the players do not cast shadows when interacting on the tabletop with their hands. Hence, interactions performed directly on the tabletop surface are best projected from the rear. However rear projection cannot be applied when augmenting real objects that are placed on the table. In this case projection from the top is used on order to augment real objects with projected textures.

Overlaying two images on the table's surface using both projectors at the same time can create effects that are not possible in any other way. Rear-projected objects can be hidden under very bright areas due to the top projector creating a scenario where users have to shade certain areas in order to see the hidden content. This can also be used the other way round: the location of virtual game pieces occluded by physical objects can be indicated by projecting hints from above.

Figure 7 shows a screenshot of one level of our application. Both the bright and the dark areas show the same area in the virtual environment. The bright

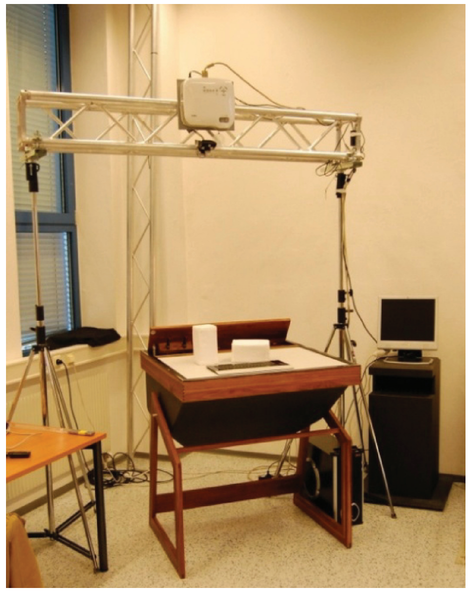


Fig. 6. Two projectors mounted inside the table and on the ceiling are used for the *IncreTable* project; the depth camera tracks the surface.

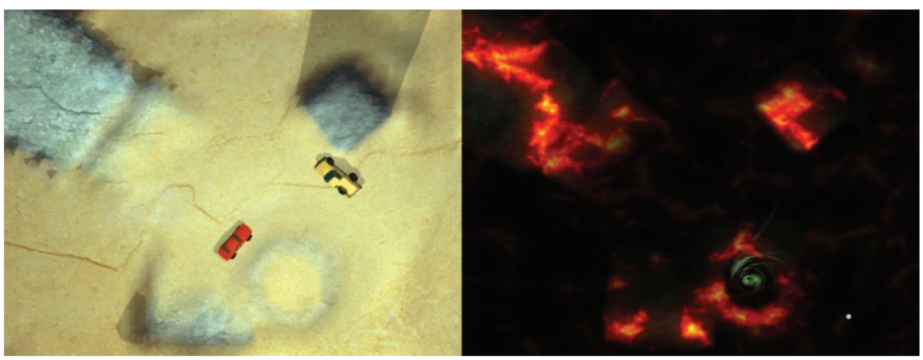


Fig. 7. Two different images are projected on the top surface and from the rear projection screen.

image on the left is projected from the top, augmenting the real objects on the table. The right area is projected from the rear and lights up areas where objects are on the table. This way, the parts of the table that would usually be in the shade still show the game environment.

The textures of the virtual terrain change dynamically, depending on the depth information obtained by the depth camera. Up to four textures are blended into one another, depending on height information.

Direct user input in *IncreTable* is implemented through the use of digital pens.

Figure 8 shows the different layers used for tracking the pen interaction on the table, which was presented in [Brandl et al. 2007]. The digital pen (with its embedded camera) tracks the Anoto-pattern printed on a special backlit foil (b).

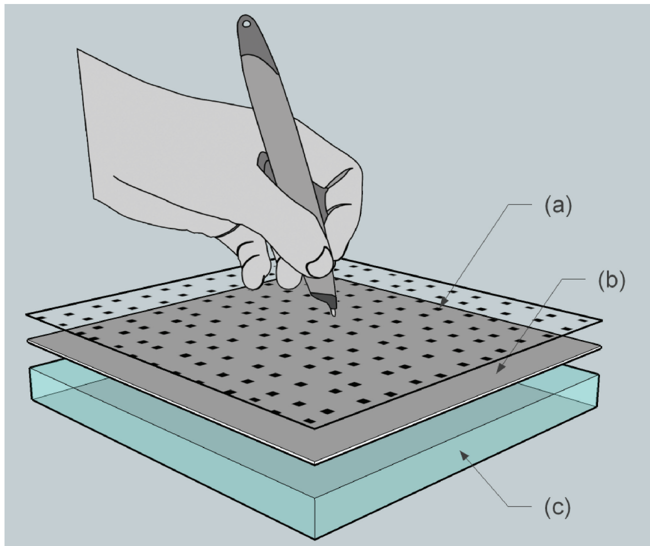


Fig. 8. The three layers of the interactive surface: the Anoto pattern (a) is printed on HP backlit UV (b), which also functions as the projection surface; a clear sheet of acrylic (c) is used as a base layer.

This foil diffused the illumination from the rear LCD projector resulting in an image with no hotspots visible at the front of the screen. The acrylic surface served as a rigid base (c) for the backlit foil (b).

In our setup, we used Maxell DP-201 digital pens from Anoto, which sends stroke data via Bluetooth to a PC. Anoto-based digital pens are ballpoint pens with an embedded infrared camera that tracks pen movements. The pen has to be used on paper with a special pattern printed on top. This pattern is printed with 600dpi and consists of small dots with a nominal spacing of 0.3mm.

The pen uses an embedded image-processing chip to calculate its absolute position on the pattern by using the captured frames. Once illuminated by the IR-LED, which is also embedded in the pen, the Anoto dot pattern appears dark (carbon-based ink is absorbing the IR light). The optimal base-material (reflecting the IR light) appears bright, resulting in a high contrast image. For optimal tracking results, the IR-camera built into the digital pen must capture high contrast images. If the material is too transparent or too glossy, the contrast between background material and dot pattern is not high enough to ensure robust pen tracking.

Our setup utilizes a special rear projection foil suitable for both top and rear projections, as well as digital pen tracking and for use with a 3D camera, while being relatively durable.

To connect the virtual and real domino blocks, we implemented special physical interfaces, the so-called portals. These special portals are currently placed at a fixed location in the virtual environment and indicate where the physical interface should be placed by the players for the chain reaction to work as intended. Future implementation could incorporate marker recognition for the

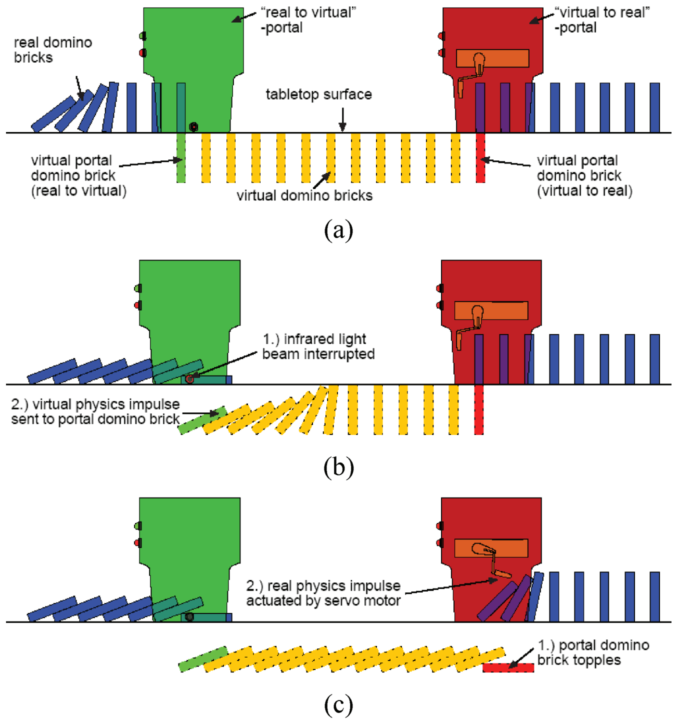


Fig. 9. Special "portal dominoes" act as virtual counterparts to the physical interfaces, allowing the transition from the real to the virtual world and vice versa.

tracking of the portals on the table. Figure 9 illustrates the interaction between virtual and real domino bricks in *IncreTable*.

Both functions, that is, the pushing of domino stones and the detection of falling domino stones, have been implemented in one single portal. To push domino stones, the portal has a rotating arm that is controlled by a micro controller unit (MCU). The MCU communicates with a PC over a Bluetooth module.

In addition, the MCU can detect the reactions of domino stones by an infrared (IR) photo-interrupter. So the portal can perform as an interface between the real world and the virtual world. Figure 10 shows a block diagram of the portal.

In *IncreTable*, we also use real robots, which can be moved with augmented fiducial markers that are projected on the rear-projection screen (see Figure 11). The robot can also be used as a bridge between the digital content and the physical world (e.g., they can hit the physical domino tiles). Each robot is equipped with five brightness sensors in order to calculate relative displacement between robot and the marker image; the robot is programmed to follow the marker image by feedback control. Thus, we can move the robots by simply moving the fiducial markers. In the game, the robots either follow predefined paths or are controlled by the player though pen input or game pad input.

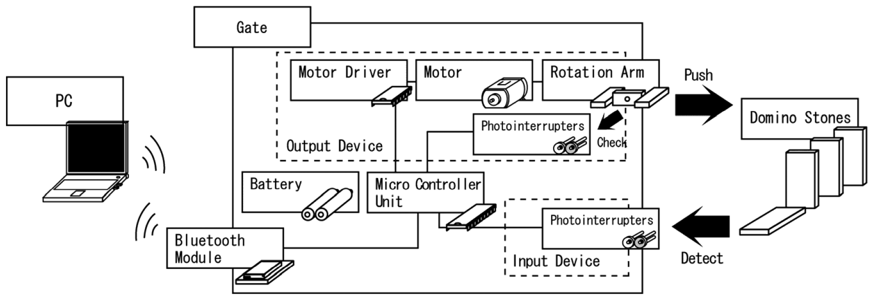


Fig. 10. Block diagram of portal domino bricks.

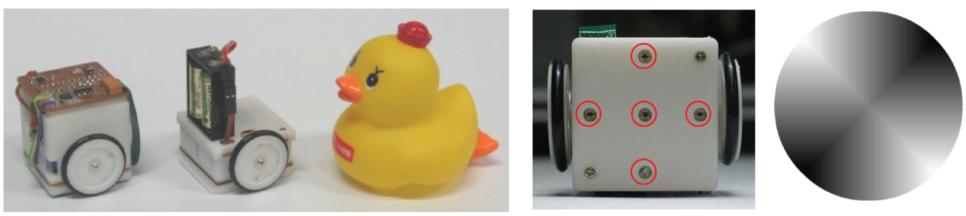


Fig. 11. The robot can have different shapes and sizes. The brightness sensors (marked with a circle) are tracking the fiducial marker that is projected on the surface, and according to the projected position, the robot can be moved.

In contrast to the robots presented in [Leitner et al. 2008], we improved the size and the weight of the robot (cf., Table I) as well as the fiducials for achieving a better performance in speed and accuracy.

Figure 12 shows the marker including the five values captured by the sensors attached to the bottom side of the robot. Four out of five brightness values are used for calculating the relative position and direction between the robot and the marker image.

The values a1, a2, a4, a5 are each sensor's output values, and, using the presented equations, the robot knows the relative displacements. The differences dx and dy on the x- and y-axes and the angle differences $d\theta$ are calculated as follows:

$$dx = a_1 - a_5$$
$$dy = a_4 - a_2$$
$$d\theta = a_1 - a_4 + a_5 - a_2$$

After the normalization of the brightness value, dx and dy can be accurately calculated from the fiducial marker and the robot can move along the x- and y-axes. Robot control is based on the coordinate system of the projectors. In that sense, the control method brings good symbiosis between graphical effects and robot motions.

The digital pen and robot, as physical artifacts by themselves, provide physical conformity in conjunction with mixed-reality experience. Similarly, the space itself around the table enables unique interaction by the localization of any objects inside it. The physicality of those objects can be captured by

Table I. Specifications About the Robot

Dimension	40mm × 40mm × 40mm
Weight	90g
Driving system	differential wheel drive
MPU	PIC16F876A(16MHz)
Sensor	TOSHIBA TPS615 × 5
Actuator	micro geared DC motor × 2

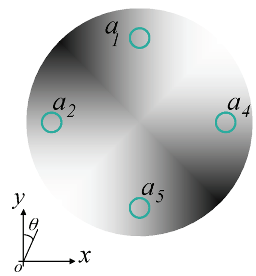


Fig. 12. Equations for calculating relative displacements.

assessing a depth image of the scene. ZCam, a depth-sensing camera manufactured by 3DV Systems, is mounted on the ceiling and provides information about the space right above the table. While more sophisticated gesture interaction scheme based on spatial properties of such a space might be usable [Yun 2009], our system concentrates on more direct use of depth images. Specifically, the shape deformation of terrain in the virtual world is triggered by the height of objects placed on the table. This is another important aspect that advances the notion of mixed reality.

The resulting depth image of 320 by 240 pixels (or 160 by 120 pixels for faster processing) in 8-bit format is sufficient to discriminate relatively small objects if their height difference is well above the resolvable depth, practically around 5 to 10 cm, which is slightly higher than the theoretical 1 to 2 cm. Its frame rate, 30 or 60 fps, depending on the resolution, also guarantees real-time interaction. Under such a circumstance, users can adopt any kind of physical objects such as rubbery blocks or paper-folded ramps to modify the virtual terrain. Figure 13 depicts an exemplar setup of the table with some objects and how they deform the corresponding terrain. Two virtual vehicles react in accordance with proper physics simulation against the real objects on the table. Note that the rubber ramps did make visible deformation, while portals and domino blocks did not due to low reflectance property and small size, respectively. Yet their small presence in the virtual counterpart is not problematic, as the portals and dominos have their own mechanical link for mixed reality, as described in the previous section.

The depth-sensing capability relies on measuring the time of the flight of infrared rays emitted by the camera. When colliding with an obstacle, the ray reflects back to the sensor. Thanks to a very high-speed shutter, the arrival time of each ray can be seen precisely. A depth value of each pixel can then be calculated from the total time of a round trip of a ray. The value scales from

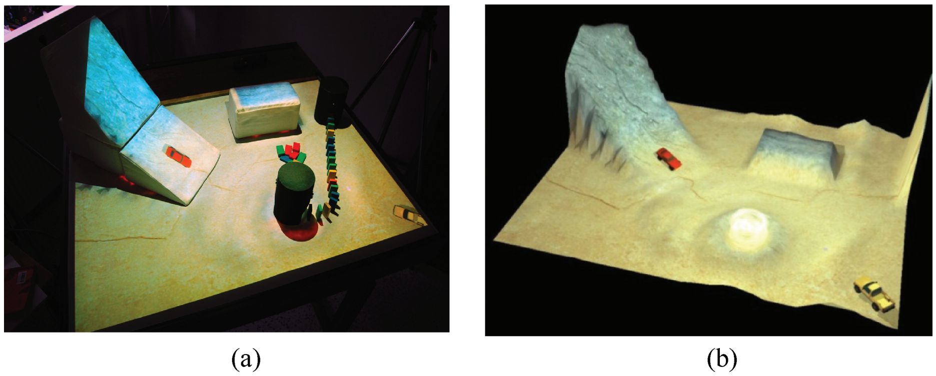


Fig. 13. (a) The tabletop surface loaded with some physical objects such as portals, rubbery blocks, and domino blocks; (b) the virtual scene with a terrain deformed by the corresponding depth image.

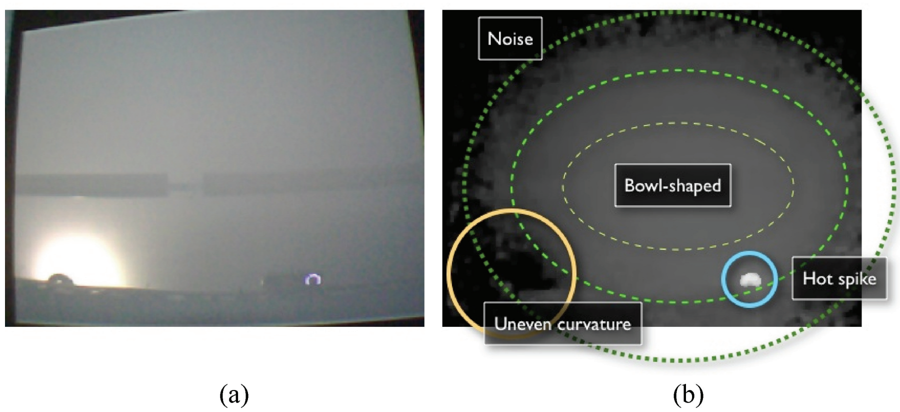
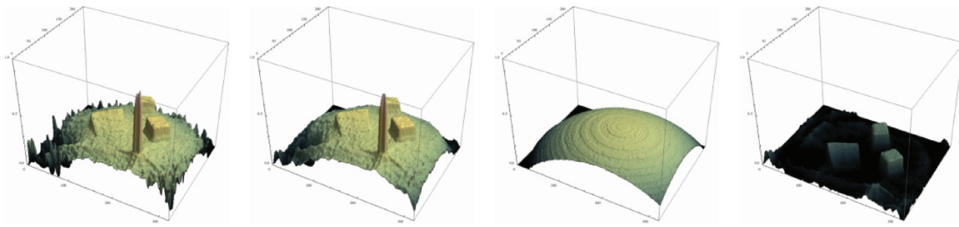


Fig. 14. (a) A color image of a reflexive table surface due to the cover glass that protects the Anoto patterns. A bright spot on the left side came from a nearby light stand, while a small circular shape on the right side was formed by a mirrored image of the camera itself; (b) a corresponding depth image revealed four types of artifacts: a noisy, bowl-shaped surface with uneven curvature and a hot spike.

0 to 255 levels, which is suitably represented in a gray-level image. This depth image, however, is susceptible to several artifacts that often distract stable interaction. Figure 14 illustrates some artifacts that appeared in a certain scene.

One of the most apparent effects is that of temporal noise on the depth values. As the built-in spatial smoothing filter was not effective enough, an accumulation filter was employed for temporal smoothing. The accumulation ratio can be tweaked for a balance between stability and responsiveness of interaction.

Another issue is the depth fall-off caused by vignetting from depth-sensing optics. Also, the perpendicular position of the camera towards the table surface tends to emphasize this effect, as a large number of rays might bounce back from the center area while many others from the boundary area might diffuse,



(a) (b) (c) (d)

Fig. 15. (a) An original depth image of the scene with three objects placed on the flat surface; (b) a pre-processed image with less noise; (c) a depth model representing the amount of compensation needed for the depth fall-off; (d) the final calibrated image without a hot spike or an erroneously curved surface. It is now clear that three objects are placed on a flat surface.

and cannot be sensed by the camera. Hence, the depth image of a flat table surface is often seen as a bowl shape, not as a plane.

Peculiar reflectance properties of the table surface also affect the quality of the depth image. Strong illumination from nearby lighting sources may negate the reflection of infrared rays, resulting in an uneven curvature of the depth surface. Sometimes, an infrared emitter of the camera is directly mirrored on the glossy surface, marking a notable peak, or hot spike, in the depth image.

As these artifacts can be interpreted as false geometric deformations, they should be eliminated to the extent that ensures natural user interaction. Hence, a depth calibration process $\bar{D}_t = p(f(D_t)) - M_t$is designed to leverage all the artifacts described above. D_t is an original depth image at time t. $\bar{D}_t$ is a calibrated depth image without artifacts. M_t is a depth model representing the number of depth levels necessary for the fall-off compensation in recovering the original flat surface from a deficient one. Modeled as a quadratic surface, it is initially fitted by the linear least squares method using samples from a depth image of the table surface without any object placed on it. f is a pre-processing step for the accumulation filter described above. p is a postprocessing step for removing hot spike glitches. It is accomplished by applying an image in-painting algorithm after detecting a peak blob using a Laplacian filter. The final calibrated image $\bar{D}_t$ is then acquired by subtracting the current depth model M_t from the processed image $p(f(D_t))$. Figure 15 shows intermediate results and a calibrated depth image of a scene with three objects.

As our system is for real-time interaction, the calibration process should be able to handle a stream of depth images, and not only one image. After user interaction is initiated, some physical objects may be placed on the table, breaking the flat surface condition assumed for calibration. Therefore, the depth model has to be carefully updated, while excluding depth values from the nonsurface area. A simple heuristic is adopted for such a task. With a depth value $D(x)_t$ of a given pixel position x at time t and a threshold δ, the location is classified as being on the surface if it satisfies $|D(x)_t - M(x)_{t-1}| < \delta$. Otherwise, it is presumed that there are obstacles on the surface that suppress any contributions to the fitting. For our system, δ was set to 20 levels of depth for possible noise compensation.

Fig. 16. Multiple users can play together to solve the puzzle.

As each of the imaging devices employed in the system have different optical properties and physical locations, their relations should become apparent by using a conventional camera calibration approach. When the system is first configured, a sequence of chessboard patterns is displayed on the table surface by two projectors: one from the top and the other from beneath the table. After each image is captured by a color sensor of the depth camera, a homography matrix between the two images can be obtained. The perspective of one projector is then transformed into another, minimizing misalignment of the projected images. It is important to keep projected screens aligned with an area of the table surface found on the depth image.

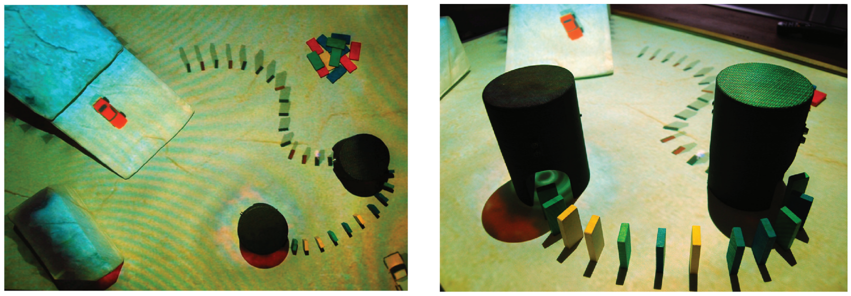
5. USER FEEDBACK

IncreTable has been demonstrated and tested at various festivals and conferences (e.g., SIGGRAPH ETech (2008), Virtual Laval (2008), RTT conference (2008)). The participants' reactions were highly positive overall. Users really liked the idea of playing with a tabletop interface that combines the real physical objects with a digital (augmented) environment. The interface was perceived as very responsive and intuitive.

Using real objects in the game also worked as a catalyst for more people to try the game. Compared to other projects, which were played in a purely virtual environment, the combination of real and virtual game components also encouraged very young children and elderly people to get involved in the game.

IncreTable also encouraged close collaboration among players (see Figure 16). In order to solve the task, all the players have to discuss their strategies and be aware of what their co-players are doing. Users also had no problems in using the digital pens to place the virtual domino pieces. The tracking results of the Anoto pens are fast and allow users to perform an accurate interaction.

One of the design goals was to avoid the use of head-mounted displays (HMDs) and heavy and cumbersome devices for tracking user head positions and orientation. Consequently, we had to find a rendering perspective suitable for tabletop projection that still looked fine for most perspectives. If the users look at the scene from a really flat angle, they would have a distorted view of



(a) (b)

Fig. 17. From the top view it is hard to distinguish between the real domino stones and the augmented stones (a). In contrast, if the user is looking at the scene from a really flat angle, the digital domino stones (in the back) are viewed from a different angle (b).

Fig. 18. The use of shadows helps a lot in estimating the distance from the car to the table's surface.

the scene (see Figure 17(b)). However, in no case was this reported to be a big problem for the players.

During our demonstrations, we noticed that the augmented shadow was observed to be a really essential part for getting a better understanding of the distance between the jumping car and the terrain (see Figure 18).

Finally, Figure 19 depicts the interaction while using the transparent tangible toolbar (e.g., the control panel), which allows users to interact with the game (e.g., to change the interaction mode). Like the tabletop surface, the toolbar can be used with the digital pens. Since only one toolbar was present during the demonstration sessions, people reported having some problems in finding the toolbar or quickly accessing the necessary tools when other players were using the toolbar at the same time.

6. EXPERIMENT

To identify problems and get more feedback on the intuitiveness of the interfaces integrated in the game, we invited people for an observational study. All sessions were recorded on video in order to gather additional information after the actual session. We used two cameras so as not to restrict users from moving freely around the table.

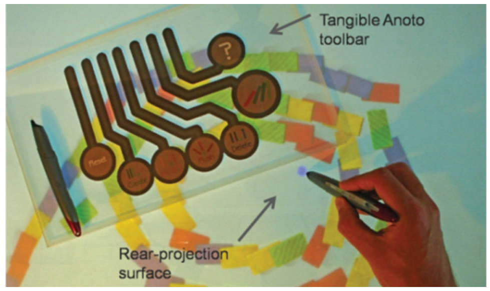


Fig. 19. The transparent tangible toolbar allows participants to use special functions. Again, on top of the plexiglass, we put a pattern marker, which can be tracked easily with the digital pen.

The table surface has a total size of 120cm × 70cm with an embedded interactive screen area of 90cm × 67.5cm. The height of 85cm allows for easy reach across the entire table surface while standing at the table. The interactive content is rear-projected onto the table surface with a total resolution of 1024 × 768 pixels.

Based on observations made prior to the study and also during four pilot studies, it was decided for the experiment to focus only on the interaction with the digital pens and the portals so as not to overwhelm users with too much information. Also, the gameplay and level of difficulty were slightly modified based on initial observations from our pilot tests. The changes were introduced in order to let players play and finish the game within a reasonable amount of time, without extensive help from the experimenters.

The changes introduced additional hints as to where to place the portals in the level as well as the color-coding the physical portals. Only a limited set of interaction modes were available to the players, and the game would not progress automatically to the next level upon finishing the current one. Also, an entirely new level trial level was developed to introduce the physical portals, while still providing enough room for users to learn how to use the pen. Even though the original game was about skill and patience, a timer was also introduced to the game to provoke faster user interactions and keep trial times shorter.

We invited 18 undergraduate students (7 males and 11 females) from two local universities to participate in this experiment. Each participant was given bonus credit in their final grades. We divided them randomly into six groups, with three people in each group.

The study was conducted with groups of three participants and lasted approximately one hour per group. The participants were shown the table and the interface was explained to them. They were shown how to use the stylus and how to switch between different modes using the tangible menus. The experimenters also explained the goal and showed the participants the start and end dominoes at each level. The participants were also shown the portals and the real domino stones; but they were not given further instructions on how the portals worked in order to provoke experimentation and discussion.

The task itself consisted of two stages. First the participants were allowed to practice the usage of all equipment for ten minutes, with an additional five

(a) (b)

Fig. 20. The setup as presented to the users at the start of the trial-session (a); and just before starting the chain reaction in the test-session (b).

(a) (b)

Fig. 21. While some participants were highly active in solving the problem (a); some of them played alone and were not able to solve the puzzle (b).

minutes in case they wanted to keep on playing. Depending on the performance of the group, hints on how to use the system were given to the group after the first ten minutes.

Upon finishing the test run, the participants were shown the actual trial level (see Figure 20(b)). The start and end dominoes were shown and the participants were asked to set up the chain of dominoes; again, ten minutes were allotted to the participants.

Before conducting the experiment, we asked all participants to read the experiment instructions. We also recorded the process of the experiment by taking photos and by recording both sound and video.

7. RESULTS

Based on our observations, we identified several problems caused by the integration of physical artifacts and nontrivial physical interfaces. Pinelle and Gutwin [2007] make a very important distinction between group activities while analyzing tabletop applications: *taskwork*, describes actions taken to complete a certain task, and *teamwork*, describes actions to complete a task taken

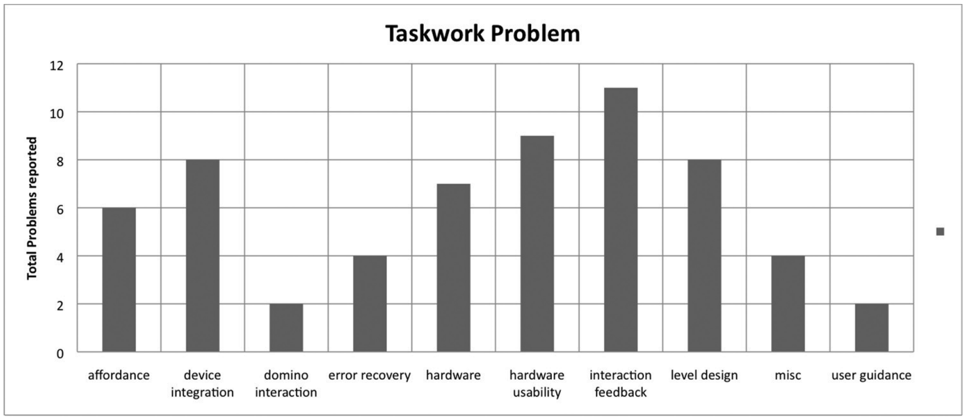


Fig. 22. Taskwork problems reported by the participants.

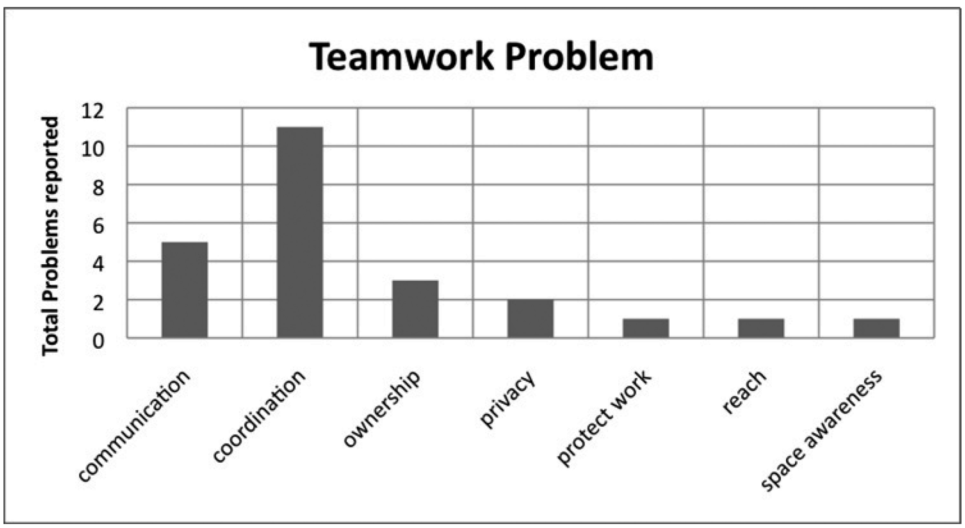


Fig. 23. Teamwork problems reported by the participants.

as a group. Taskwork problems included affordance problems, (e.g., when the participants had difficulties interpreting the arrows on the gates), or had level-design problems (e.g., when the timer was not placed optimally). (See Figure 22)

Teamwork problems (cf., Figure 23) included communication, coordination, ownership, privacy; work protection, reach, and space-awareness problems:

- *Communication* problems refer to when, for example, a nondominant player's accomplishments were not noticed and/or forgotten during a session (see Figure 20).
- *Coordination* refers to problems when participants could not coordinate parallel tasks and undertook actions without synchronizing with each other.
- *Ownership* problems occurred when, for example, participants were moving freely around the table and forgot their personal input device.

- *Privacy* problems were identified when participants removed the gates from other participants.
- *Work protection* problems refer to a participant leaning on the table to cover up his or her work.
- *Reach* problems occur when participants do not move around the table and when they could not set up domino stones on the other side of the table.
- *Space-awareness* refers to problems that occurred when participants did not recognize that their partners were moving to different areas of the table.

The following list provides several examples of problems that were identified during the evaluation:

- Participants did not understand how to use the physical interface at all.
- Participants did not understand how physical artifacts interact with the virtual game world through the physical interface.
- Moveable parts of the physical interface that did not have any effect in the virtual world were interpreted as interfaces.
- Physical interface actions could not be activated by users because they did not understand the connection between the physical and the digital worlds.
- Participants could change functions of the physical interface that were not recognized in the virtual world.
- After a correct initial setup, participants changed the position of the physical interfaces due to missing positive feedback.
- Features of the physical interface indicated functionality not supported by the physical interface.
- Physical interfaces obstructed relevant game parts and hindered game interaction.
- Malfunctioning physical interfaces were not recognized by the system.

Summarizing our observations, we noticed that most of the problems were caused

(1) by misleading design of the physical interface (affordance of the interface);
(2) by a missing link between the physical interface and the application (positive/negative feedback);
(3) or by occlusion of a game-relevant part of the tabletop surface through physical artifacts;

By looking at these three categories of problems more closely in the future, we hope to create a more enjoyable experience. We also noticed several issues not connected to the physical interfaces we used in our game. The following list provides several additional observations in regard to how players negotiated the interfaces and space around the table:

- Users (unintentionally) took other players' input devices after misplacing their own devices on the table.

(a) (b) (c)

Fig. 24. (a) One participant is moving into the territory of another participant; (b) one participant takes the device away from another participant.

- At times, users did not forward their personal devices although other participants asked them to do so.
- Players were forced out of the way to accomplish a task rather than asking the other person to hand-off an area or to help with the task (see Figure 24(a)).
- Users obtained private tools by taking them from another person (see Figure 24(b) and (c)).

We are not confident that these incidents were caused by the fact that users behave differently while playing games, and it would be interesting to compare our results with those performing a similar experiment.

8. CONCLUSIONS AND FUTURE WORK

In this article, we have presented a new tabletop game, in which both the real and digital worlds have to be connected to solve various puzzles in the game. The *IncreTable* game allows users to play with real and digital domino tiles, physical robots, and virtual cars. The first informal observational studies at various exhibitions showed that the integration of digital content into the real environment was considered an entertaining and interesting concept.

Our ongoing work will continue to add additional interfaces to the game in order to explore the possibilities of multimodal interfaces in tabletop scenarios even further. Moreover, we are planning to continue with formal user studies for tabletop games to improve future applications.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to all the participants in the user study, and to Thomas Seifried and Peter Brandl for discussion and feedback.

REFERENCES

Bakker, S., Vorstenbosch, D., Van Den Hoven, E., Hollemans, G. and Bergman, T. 2007. Weathergods: Tangible interaction in a digital tabletop game. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction* (TEI'07). ACM, New York, 151–152.

Barakonyi, I., Weilguny, M., Psik, T., and Schmalstieg, D. 2005. MonkeyBridge: Autonomous agents in augmented reality games. In *Proceedings of the 2005 ACM SIGCHI International*

Conference on Advances in Computer Entertainment Technology (ACE'05), vol. 265. ACM, New York, 172–175.

BRANDL, P., HALLER, M., HURNAUS, M., LUGMAYR, V., OBERNGRUBER, J., OSTER, C., SCHAFLEITNER, C., AND BILLINGHURST, M. 2007. An adaptable rear-projection screen using digital pens and hand gestures. In *Proceedings of the IEEE ICAT 2007*, 49–54.

BUISINE, S., BESACIER, G., NAJM, N., AOUSSAT, A., AND VERNIER, F. 2007. Computer-supported creativity: Evaluation of a tabletop mind-map application. In *Engineering Psychology and Cognitive Ergonomics,* LNCS 4562, Springer, Heidelberg, 22–31.

DIETZ, P., UND D., AND LEIGH. 2001. DiamondTouch: A multi-user touch technology. In *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology,* ACM, New York. 219–226.

GREENBERG, S., UND C., AND FITCHETT. 2001. Phidgets: Easy development of physical interfaces through physical widgets. In *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology* (UIST'01). ACM, New York, 209–218.

KOJIMA, M., SUGIMOTO, M., NAKAMURA, A., TOMITA, M., INAMI, M., AND NII, H. 2006. Augmented Coliseum: An augmented game environment with small vehicles. In *Proceedings of the First IEEE International Workshop on Horizontal Interactive Human-Computer Systems* (Tabletop). IEEE, Washington, DC, 3–8.

LEE, W., WOO, W., AND LEE, J. 2005. TARBoard: Tangible augmented reality system for table-top game environment. In *Proceedings of the International Workshop on Pervasive Gaming.*

LEITNER, J., BRANDL, P., SEIFRIED, T., HALLER, M., YUN, K., WOO, W., SUGIMOTO, M., AND INAMI, M. 2008. IncreTable, bridging the gap between real and virtual worlds. In *International Conference on Computer Graphics and Interactive Techniques.* ACM, New York.

LEITNER, J., KÖFFEL, C., AND HALLER, M. 2009. Bridging the gap between real and virtual objects for tabletop games. *Int. J. Virtual Reality 7*, 4, 33–40.

LOENEN, E. VAN, T. BERGMAN, V. BUIK. VAN GELDER, M. GROTEN, G. HOLLEMANS, J. HOONHOUT, T. LASHINA AND VAN DE WIJDEVEN. 2007. Entertaible: A solution for social gaming experiences. In *Proceedings of the Tangible Play Workshop, Intelligent User Interfaces Conference*, 16–18.

MAGERKURTH, C., MEMISOGLU, M., ENGELKE, T., AND STREITZ, N. 2004. Towards the next generation of tabletop gaming experiences. In *Proceedings of the Graphics Interface Conference*. ACM, New York, 73–80.

MAGERKURTH, C., STENZEL, R., AND PRANTE, T. 2003. STARS - A ubiquitous computing platform for computer augmented tabletop games. In *Proceedings of the 5th International Conference on Ubiquitous Computing*.

MANDRYK, R. L. AND MARANAN, D. S. 2002. False prophets: Exploring hybrid board/video games. In *Extended Abstracts on Human Factors in Computing Systems* (CHI'02). ACM, New York, 640–641.

MELLIS, D. A., BANZI, M., CUARTIELLES, D., AND IGOE, T. 2007. Arduino: An open electronics prototyping platform. In *Proceedings of the Conference on Human Factors in Computing* (CHI'07). ACM, New York.

PINELLE, D. AND GUTWIN, C. 2007. Evaluating teamwork support in tabletop groupware applications using collaboration usability analysis. *Personal Ubiquitous Comput.12*, 3, 237–254.

SCOTT, S.D. AND CARPENDALE, S. 2006. Guest editors' introduction: Interacting with digital tabletops. *IEEE Comput. Gr. Appl. 26*, 5 (Sept./Oct.), 24–27.

TSE, E., GREENBERG, S., SHEN, C., AND FORLINES, C. 2007. Multimodal multiplayer tabletop gaming. *Comput. Entertain. 5*, 2 (April), 12.

WILSON, A. 2000. PlayAnywhere: A compact tabletop computer vision system. In *Proceedings of the Symposium on User Interface Software and Technology* (UIST).

WILSON, A. 2007. Depth-sensing video cameras for 3D tangible tabletop interaction. In *Proceedings of the 2nd IEEE International Workshop on Horizontal Interactive Human-Computer Systems* (Tabletop 2007).

YUN, K. AND WOO, W. 2009. Tech-note: Spatial interaction using depth camera for miniature AR. In *Proceedings of the* IEEE *International Symposium on 3D User Interfaces* (3DUI), 119–122.

Received June 2009; accepted August 2009